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Comparative study of optimization algorithms for sizing of Wind Turbine/ Fuel Cell/ Electrolyzer/ Hydrogen Tank in the hybrid stand-alone power system

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Abstract

In this paper, a comparative study of optimization algorithms for determining the optimal size of hybrid stand-alone power systems at the lowest total cost is proposed. In this regard, the performance of the components of hybrid power system including wind turbine, fuel cell, anaerobic reactor, reformer, electrolyzer and hydrogen tank has been studied and several different optimization algorithms are taken into account. The proposed method can meet the load demand using wind energy and biomass as an available energy resource. In the stand-alone power system, power produced by the wind turbine and fuel cell (fed by the reformer) are applied to the demand. When these generations are more than the demand, additional power is delivered to the electrolyzer. Otherwise, the hybrid system is fed by the hydrogen tanks. The proposed method has been tested in Kahnooj region located in the southeastern of Iran and the results of various optimization methods have been presented in order to determine the optimal size of the hybrid power system.

Keywords: Biomass, Fuel cell, Hydrogen tank, Optimization methods, Wind turbine.

1. INTRODUCTION

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1.1. Motivation

Global environmental concerns, the increasing need for energy and progressive of renewable energy technologies, have led to the development of new formats for the public use of renewable energy sources (RESs) [1]. In particular, advancements in the technology of wind and fuel cell energy have increased the use of these energy sources to generate electricity as stand-alone or grid-connected. The share of fossil energy sources among other energy sources for electricity generation in centralized systems is very significant. The large size of production units, the distance from production to consumption centers and high environmental pollution are the most important features of conventional power generation systems. Nowadays, the use of renewable energies is growing and evolving, and in most cases, a combination of these resources is used in applications stand-alone and remote areas [2]. Unfortunately, many consumers, in various countries, cannot be connected to the national electric grid [3]. This stems from different reasons, happening mainly due to technical constraints, such as impasse the region or economic, being away from generation centers and having low population. In these areas, the need for energy, especially electricity, can be met by utilizing existing energy sources, which are mainly renewable energy sources such as wind, biomass and solar energy. Applying only one energy source, for example wind energy, drives the distributed generation system to a variable generation system, which significantly reduces the reliability. Wind energy significantly fluctuates within seasons and years. As a result, the performance of the system will strongly vary [4]. Therefore, the combination of wind turbines with other energy sources can increase the reliability of the generation system and make the output of electrical energy almost independent of the system. Wind turbines and fuel cells could be applied in order to prevent too frequent start-ups and shut-downs. In times of the day, when wind turbines are unable to supply, fuel cells contribute to power consumption by generating electricity [5].

Since the regional area under study in this paper has good wind speed and high availability of biomass resources, the wind-fuel cell system has been proposed for the study area. In this paper, the optimal size of the wind/fuel cell system is investigated. The extra power generated by wind turbine will be delivered to electrolyzer and stored in the hydrogen tank. When there is a shortage of electricity, the fuel cell generates energy using the hydrogen stored in the hydrogen tank. In addition, the performance of hybrid power system has been studied over a year and the main objective of this paper is to determine the optimal size of the hybrid power system based on the minimization of total costs.

1.2. Literature Review

In [6], a wind turbine system coupled with a fuel cell is investigated to compensate for power fluctuations caused by wind speed variations. Part of the energy produced by the wind turbine is stored in the form of hydrogen and delivered to the consumer through fuel cell.

In [7-8], the concept of wind farm associated with superconductor magnetic energy storage (SMES) as grid-connected is examined.

In [9], a hybrid power system based on wind/solar has been proposed. When the power produced by the wind-solar system is more than the demand, the electrolyzer is switched on to start and produced hydrogen is delivered to the storage tank. If the hydrogen tank is filled, the extra power will be delivered to a local load.

The main purpose of the reference [10] is to determine the size of the photovoltaic/wind system to supply the load demand. In addition, the method of determining the size of the battery is evaluated based on the wind speed and solar radiation. The least squares method is used to determine the size of the hybrid system.

In [11], the objective is to determine the size of the hybrid power system related to solar/wind system in order to minimize the total costs including initial investment, maintenance and replacement costs and meet the constraints. The simulation results show that the proposed hybrid power system is less expensive than the solar or wind system.

In [12-14], hybrid stand-alone power systems with back-up hydrogen storage systems have been presented. These studies have investigated the integration of RESs and focused on power of these systems as “zero emissions”.

A comprehensive review of RESs in order to find the optimal size of hybrid system is given in [15-19].

1.3. Contribution and Paper Organization

This paper focuses on solving the optimal sizing and operation strategy of hybrid system in which generation rescheduling based on the number of used components obtained by different optimization methods have been taken into consideration.

As a result, the main contributions of the paper are categorized as follows:

- Modelling the problem of the optimal sizing strategy of hybrid system as a cost-based model;
- Using wind energy and biomass as an available energy resource;
- Using of the hydrogen storage in order to cover the demand and improvement of reliability;
- Implementing of simulation results for Kahnouj site in southeast Iran as far from the grid;
- Solving the problem based on variety of evolutionary algorithms;

The paper is organized as follows:

Section 2 formulates the optimal sizing of a wind-fuel cell hybrid system problem. In Section 3, solution methodology is proposed. Section 4 presents the simulation results. Section 5 concludes the paper.

2. MATHEMATICAL FORMULATION

In order to find an optimal and economical solution with minimum investment and operational cost functions, that is discounted to the present value, a mathematical formulation is needed. This problem is an optimization problem, which designs the hybrid generation system regarding equality and inequality constraints. The objective in the proposed problem is minimization of the total investment, replacement and maintenance costs related to wind/FC-based hybrid system, is as follows [9]:

$$cost_{total} = NPC_{wt} + NPC_{el} + NPC_{tank} + NPC_{fc} + NPC_{ref\&reactor} + NPC_{conv} \quad (1)$$

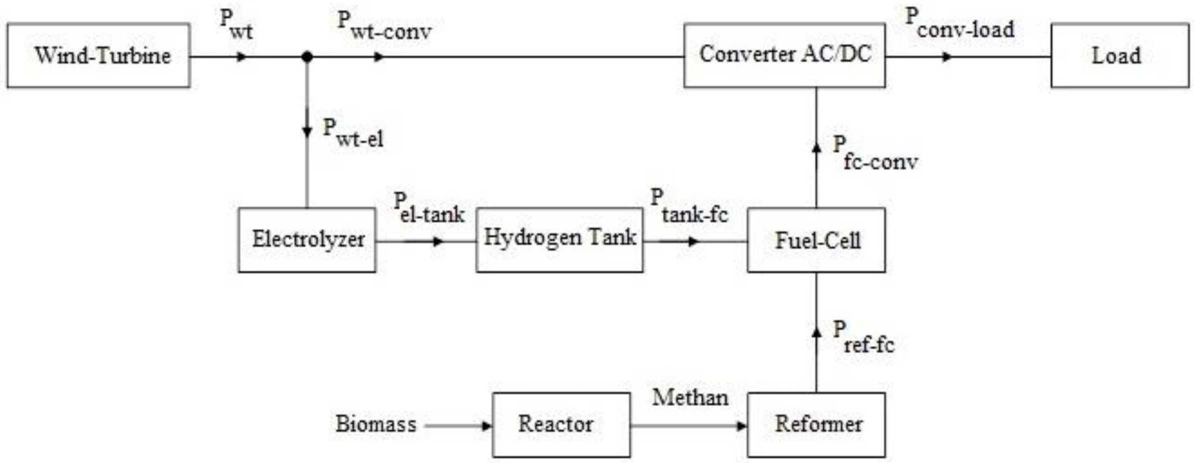

Fig. 1. The schematic of the hybrid power system.

where,

$$NPC = N \times \left(cost_{investment}\ (\$) + \sum_{n=1}^{Y} \frac{1}{(1+ir)^{L\times n}} \times cost_{replacement}\ (\$) + \left(\frac{1}{CRF(ir,R)} (year) \times cost_{maintenance} \left(\frac{\$}{year} \right) \right) \right) \quad (2)$$

In order to convert the initial capital cost to the annual capital cost, the capital recovery factor (CRF), defined by Eq. (3) is used.

$$CRF(ir,R) = \frac{ir(1+ir)^R}{(1+ir)^R - 1} \quad (3)$$

3. SOLUTION METHODOLOGY

According to Fig. 1, the electricity coming from the wind turbine (WT), is converted to AC power by an inverter in order to feed the load demand. The produced power of WT is dependent on speed–power curve and obtained as follows [20]:

$$P_{wt} = \begin{cases} 0 & V < V_{cut-in} \quad or \quad V > V_{cut-out} \\ P_{rated} \times \left(\frac{V - V_{cut-in}}{V_{rated} - V_{cut-in}} \right)^3 & V_{cut-in} \le V < V_{rated} \\ P_{rated} & V_{rated} \le V \le V_{cut-out} \end{cases} \quad (4)$$

Biomass is potentially a very important source of the hydrogen production. It consists of all plants (wood, straw, etc.) that re-grow from the Earth’s surface. The energy produced by the biomass in the form of the hydrogen by reformer is delivered for the consumption through a fuel cell [21].

During times of high wind speeds, the excess energy can be converted into the hydrogen as a gas under high pressure using an electrolyzer and it then feeds a fuel cell system.

Fig. 2 shows the framework of the proposed optimal energy management model. There are three modes for the system [22-23].

Mode 1: The power generated by the wind turbine plus the power generated by the fuel cell, which is fed through the reformer, is equal to the load demand. In this case, the electrolyzer is not produced and the system equations are as follows:

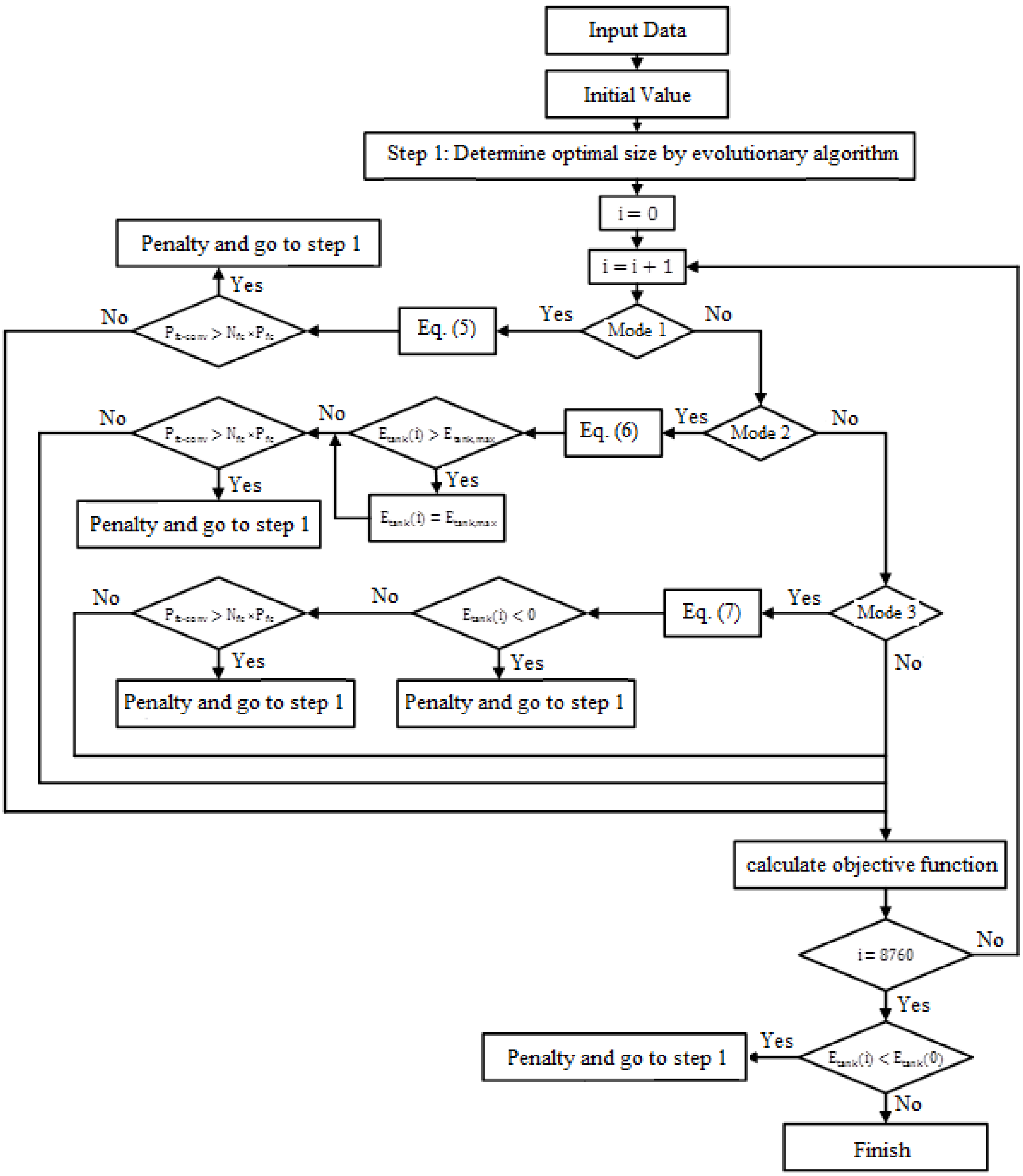

Fig. 2. The technical flowchart of the proposed method.

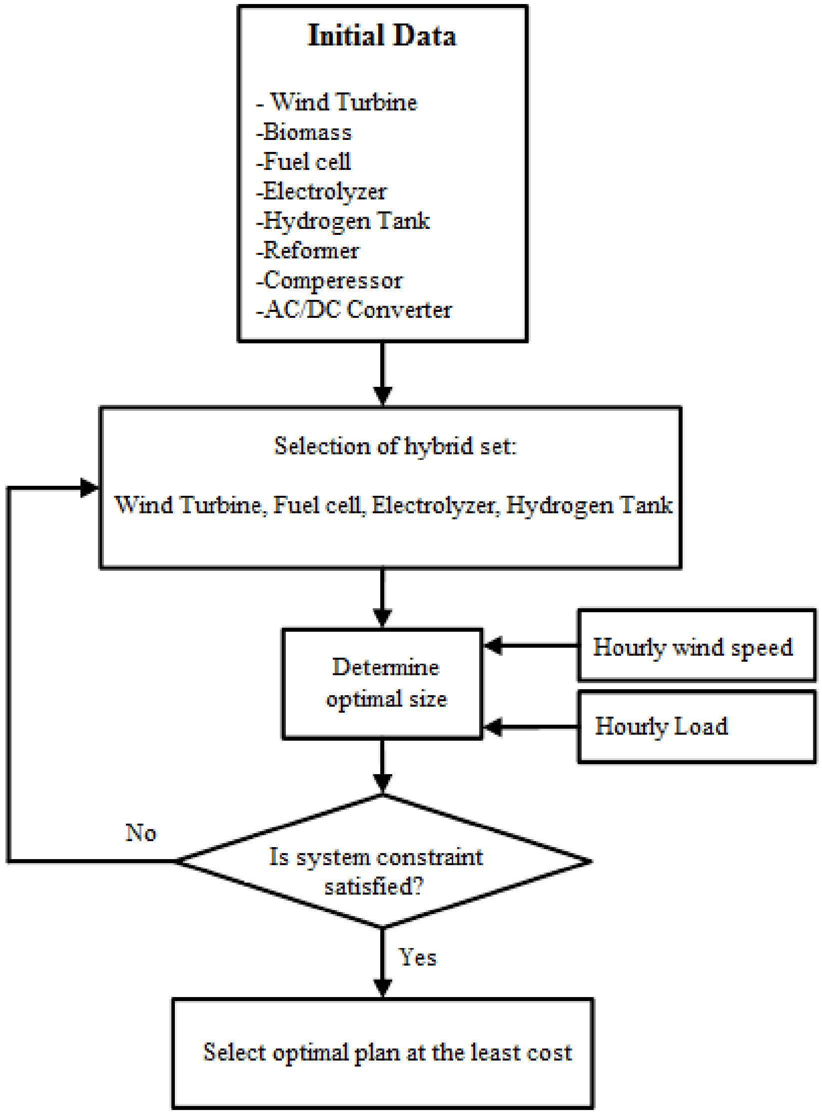

Fig. 3. The general flowchart of sizing of hybrid power system.

$$
\begin{aligned}
&P_{wt} + \eta_{fc} \times P_{ref-fc} = \frac{P_{load}}{\eta_{conv}} \\
&P_{wt-conv} = P_{wt} \\
&P_{wt-el} = 0 \\
&P_{fc-conv} = \eta_{fc} \times P_{ref-fc} \\
&P_{el-tank} = 0 \\
&P_{tank-fc} = 0 \\
&E_{tank}(i) = E_{tank}(i-1)
\end{aligned}
\qquad (5)
$$

Mode 2: The power produced by the wind turbine plus the power produced by the fuel cell, which is fed through the reformer, is greater than the load capacity. In this case, the excess power produced by the wind turbine is given to the electrolyzer, and the produced hydrogen is stored in the hydrogen tank. The equations are as follows:

$$P_{wt} + (\eta_{fc} \times P_{ref-fc}) > \frac{P_{load}}{\eta_{conv}}$$
$$P_{wt-conv} = \frac{P_{load}}{\eta_{conv}} - (\eta_{fc} \times P_{ref-fc})$$
$$P_{wt-el} = P_{wt} - P_{wt-conv} \quad (6)$$
$$P_{el-tank} = \eta_{el} \times P_{wg\_el}$$
$$P_{tank-fc} = 0$$
$$P_{fc-conv} = \eta_{fc} \times P_{ref-fc}$$
$$E_{tank}(i) = E_{tank}(i-1) + P_{el-tank}(i)$$

Mode 3: The power produced by the wind turbine, as well as the power produced by the fuel cell, which is fed through the reformer, is smaller than the load capacity. In which case, the fuel cell is also fed through the hydrogen tank to be able to supply the load. The equations are as follows:

$$P_{wt} + (\eta_{fc} \times P_{ref-fc}) < \frac{P_{load}}{\eta_{conv}}$$
$$P_{wt-conv} = P_{wt}$$
$$P_{wt-el} = 0$$
$$P_{el-tank} = 0$$
$$P_{fc-conv} = \frac{P_{load}}{\eta_{conv}} - P_{wt-conv} \quad (7)$$
$$P_{tank\_fc} = \frac{P_{fc\_conv}}{\eta_{fc}} - P_{ref-fc}$$
$$E_{tank}(i) = E_{tank}(i-1) - P_{tank-fc}(i)$$

In all the three cases, the hydrogen produced by the reformer is delivered to the fuel cell and the fuel cell produces power.

$$E_{tank}(i) = \begin{cases} 0 & E_{tank}(i) \le 0 \\ E_{tank}(i) & 0 < E_{tank}(i) < E_{tank,max} \\ E_{tank,max} & E_{tank}(i) \ge E_{tank,max} \end{cases} \quad (8)$$

In this paper, the particle swarm optimization (PSO) algorithm and several other optimization methods are used to minimize the objective function defined by Eq. (1). However, only not optimization is not just about minimizing system costs, but also the performance of the system is considered in the optimization. Thus, if the sizing of the hybrid generation system, obtained from optimization, do not meet the system constraints, they are not acceptable and will not be selected as the optimal solution.

Fig. 3 shows the general flowchart of the proposed method to determine the optimal size of the system components. As can be seen, at first, the information, related to wind turbine, the region's biomass, the electrolyzer, the hydrogen tank, the fuel cell, the reactor, the reformer, the AC /DC converter, the region's hourly load and the wind's hourly speed are entered into the proposed method.

4. SIMULATION RESULTS

In this section, the results of the implementation of the proposed program will be presented. The main goal is to determine the optimal size of the components of the hybrid system for a stand-alone network with an annual peak load of 2,000 KW.

4.1. Specifications of the Study Area and Hybrid Power System

The nominal power of each wind turbine unit is 7.5 kW, the power of each electrolyzer and fuel cell is 1 kW, the size of each hydrogen tank is 1 kg and the useful life of the project is 20 years.

This study was conducted for the city of Kahnooj in the South-east of Iran with a population of 2,000 people [24]. It is assumed that each person produces 600 grams of biomass during the day and night, and this biomass is delivered daily to the anesthesia reactor, and this reactor produces a constant amount of methane. This methane is converted to the hydrogen by the reformer. Depending on the daily amount of biomass produced, the size of the anaerobic reactor and the reformer is determined, which is a fixed number. The amount of hydrogen produced per kilogram of biomass is 0.0454 kg. Therefore, the total amount of hydrogen produced is approximately 55 kg. The amount of energy per kilogram of hydrogen is 37.8 kWh, which is equivalent to 2,079 kWh of energy. It should be noted that the size of the reactor is determined by the amount of biomass produced per day. The amount of biomass, produced in the region, is 480 kg per day. The size of the reformer is determined by the amount of hydrogen produced by the biomass per day, which is equal to 22 kg per day (0.0454×480). The input data including speed of wind turbine, technical characteristic of the components of the hybrid system and regional information in the study area are tabulated in Tables 1 to 3.

The load curve and wind speed of Kahnooj are shown in Figs. 4 and 5, respectively. It should be noted that wind speed information has been received from Kahnooj site.

TABLE 1. ***Input Data for wind turbine.***

Parameter	Value
Rated Power (kW)	7.5
Cut-in speed (m/s)	25
Rated speed (m/s)	11
Cut-out speed (m/s)	3.1

TABLE 2. ***Input Data related to the cost, efficiency and useful life of the components of the hybrid system.***

	Cost ($)			Efficiency (%)	Useful life (Year)
	Investment	Replacement	Maintenance		
Wind turbine	19400	15000	75	45	20
Fuel cell	3000	2500	0.02 (per hour)	50	40000 hour
Electrolyzer	2000	1500	20	90	7
Reformer	1450	1300	100	-	20
Hydrogen Tank	1300	1200	15	100	20
Converter	800	800	0	90	15

TABLE 3. ***Input information related to peak load, biomass and population.***

Parameter	Value
Peak Load (KW)	2000
The amount of energy per kilogram of hydrogen (KWh)	37.8
The amount of hydrogen produced per kilogram of biomass (kg)	0.0454
The amount of biomass produced by each person in one day (gr)	600
Population	2000

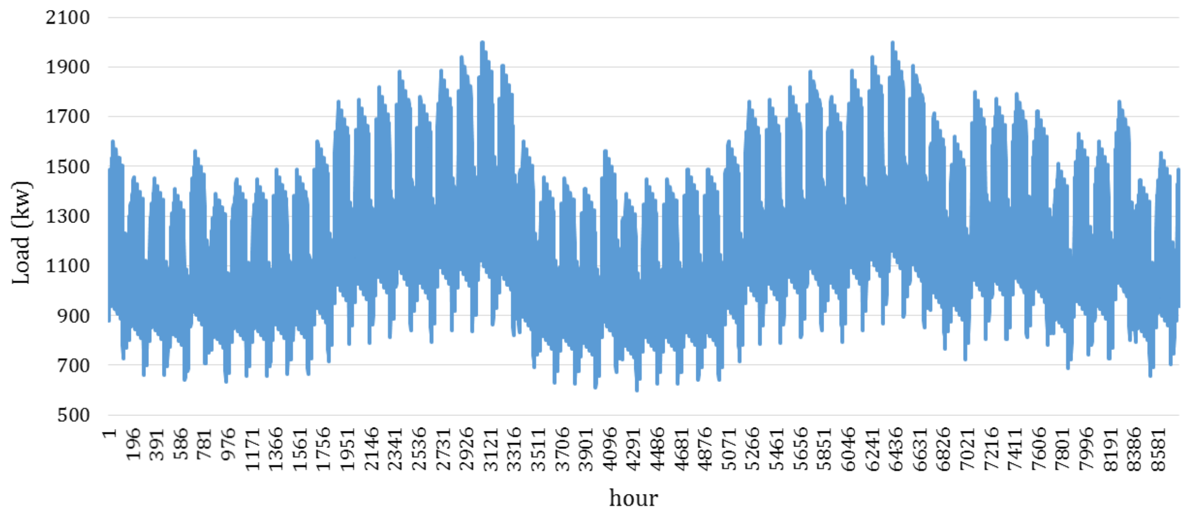

Fig. 4. Hourly diagram of load demand over a year.

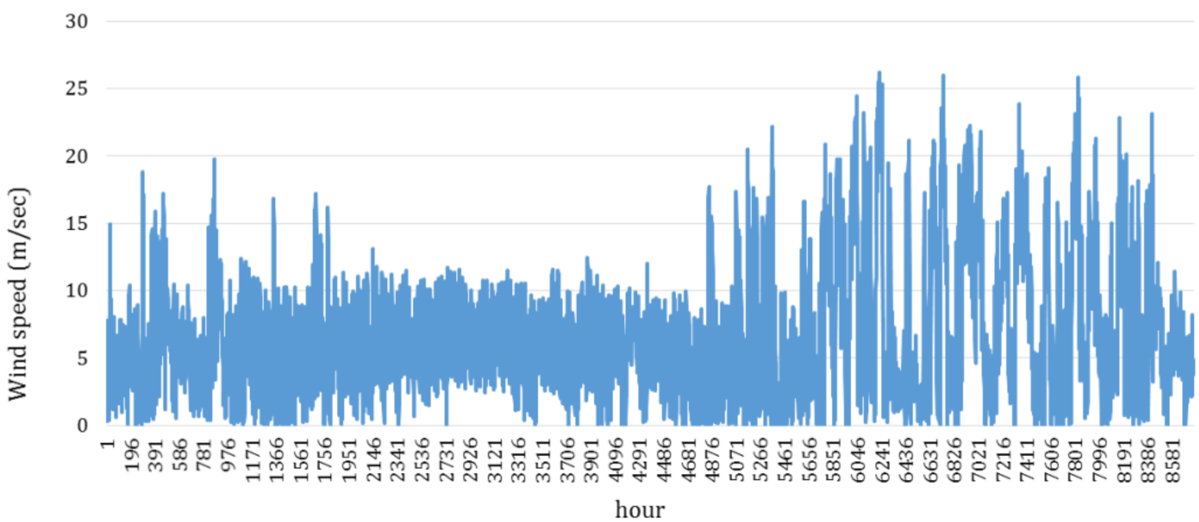

Fig. 5. Hourly diagram of wind speed over a year.

4.2. Analysis of Results

In this paper, 7 different optimization algorithms are used to determine the optimal size of the hybrid power system taking into account the system constraints. These algorithms include:

1) Particle swarm optimization (PSO)
2) Differential Evolution (DE)
3) Shuffle Frog Leaping Algorithm (SFLA)
4) Genetic Algorithm (GA)
5) Ant Colony Optimization (ACO)
6) Artificial Bee Colony (ABC)
7) Simulated Annealing (SA)

Details and principles of operation of these optimization methods are available in the reference [20]. In all of these methods, the number of iteration is equal to 100 and the number of population is equal to 60.

The values of the cost function, including the best, average and worst cost after performing these methods, are shown in Table 4. As can be seen in this table, apart from the two methods of SFLA and SA, the other methods have achieved the same number of costs. As a result, it can be inferred that the same solution is obtained from the five optimization methods, actually indicating the optimal solution to the problem, and there is no better solution than that. The number of components of the combined power system, obtained by each of these optimization methods, is shown in Table 5.

According to this table, the optimal number of wind turbines is 10, the optimal number of fuel cells is 10, the optimal number of electrolyzer is 116 and the optimal number of hydrogen tanks is 2223, and the system cost with this number of elements is equal to 7033941.8204 $.

The convergence of each of these optimization methods is also compared in Fig. 6. As can be seen in this figure, the convergence of the differential evolutionary algorithm, the genetic algorithm, and the ant colony algorithm are faster than the other methods. However, it should be noted that these results may change in different performance of these methods.

TABLE 4. ***Best results obtained by different evolutionary algorithms.***

Optimization Method	Best Cost ($)	Average Cost ($)	Worst Cost ($)
PSO	7033942	7037898	7066558
DE	7053647	7103422	7156980
SFLA	7067651	7158931	7525782
GA	7061455	7131134	7268093
ACO	7046244	7114270	7213510
ABC	7072560	7134785	7229894
SA	7323763	7712998	8129894

TABLE 5. ***The results of optimal management of hybrid power system.***

Optimization Method	No. Wind turbine	No. Fuel cell	No. Electrolyzer	No. Hydrogen tank
PSO	10	10	116	2223
DE	10	10	116	2223
SFLA	10	11	117	2224
GA	10	10	116	2223
ACO	10	10	116	2223
ABC	10	11	124	2235
SA	15	49	138	2229

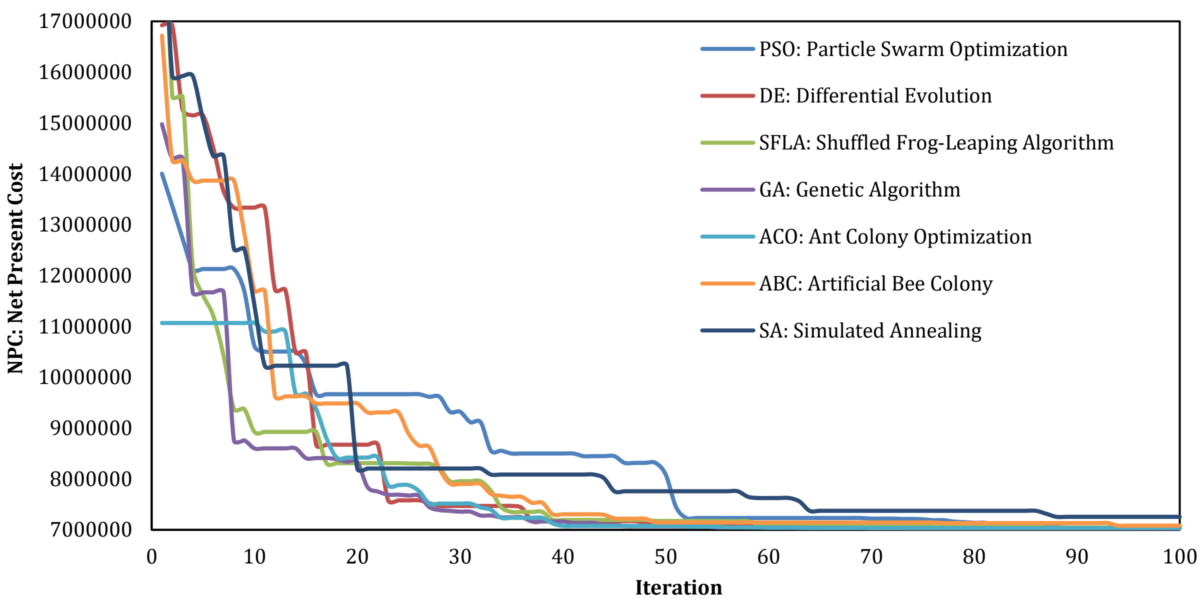

Fig. 6. Convergence behaviors of different evolutionary algorithms.

5. CONCLUSION AND FUTURE WORKS

In this paper, the optimal size of a hybrid system including wind turbine, fuel cell, electrolyzer, hydrogen tank, anaerobic reactor, reformer and converter were studied. The wind turbine and biomass were used as the primary sources of energy production. In this system, fuel cell is used as a support for wind turbine. Therefore, the system has a high reliability in loading. Hybrid power systems are the best option for covering the electrical energy required by remote areas. However, these systems have an acceptable efficiency and lower environmental pollution. Other benefits of these systems include reducing the investment costs to expand the transmission network, improving the power quality, increasing the reliability, reducing electricity purchases from neighboring countries, and eliminating the need for high-capacity power plants.

In future, the optimal sizing of a wind-fuel cell hybrid system shall be used with complex real-world application of various fields such as demand-side management and probabilistic methods to modeling the uncertainties in RESs.

NOMENCLATURE

$P_{wt-conv}$	The generated power by wind turbine to converter (kW)
P_{wt-el}	The generated power by wind turbine to electrolyzer (kW)
$P_{el-tank}$	The delivered power from the electrolyzer to the hydrogen tank (kW)
$P_{tank-fc}$	The power that the hydrogen tank delivers to the fuel cell (kW)
$P_{fc-conv}$	The generated power by fuel cell to converter (kW)
$P_{conv-load}$	The delivered power from the converter to load (kW)
P_{ref-fc}	The generated power by reformer to fuel cell (kW)
$P_{comp-tank}$	The generated power by compressor to hydrogen tank (kW)
P_{wt}	The generated power by wind turbine (kW)
P_{load}	Load demand (kW)
E_{tank}	Hydrogen stored in tank (kWh)
$\eta_{fc}, \eta_{el}, \eta_{conv}$	Efficiency of fuel cell, electrolyzer and converter
NPC_{index}	Net present cost (the index shows the corresponding component)
ir	Interest rate
N_{index}	The optimal number of the system components
$cost_{investment}$	capital cost
$cost_{replacement}$	replacement cost
$CRF(ir, R)$	capital recovery factor
$cost_{maintenance}$	operation & maintenance cost
V_{cut-in}	cut-in wind speed (m/s)
$V_{cut-out}$	cut-out wind speed (m/s)
V_{rated}	nominal wind speed (m/s)
E_{tank}	Stored energy in the hydrogen tank
PSO	Particle swarm optimization
DE	Differential Evolution
SFLA	Shuffle Frog Leaping Algorithm
GA	Genetic Algorithm
ACO	Ant Colony Optimization
ABC	Artificial Bee Colony
SA	Simulated Annealing
RESs	Renewable Energy Sources
SMES	Superconductor Magnetic Energy Storage

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